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Optimized Coordination of Directional Relays using PSO with Enhanced Penalty Factor based Fitness Features

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***Abstract*-Optimization of directional over-current relay (DOCR) settings is an important problem in electrical engineering. The optimization model of the problem turns out to be non-linear and highly constrained in which two settings namely time dial setting (TDS) and plug setting (PS) of each relay are considered as decision variables; the sum of the operating times of all the primary relays, which are expected to operate in order to clear the faults of their corresponding zones, is considered as an objective function. In the present study, model considered namely IEEE 8-bus model. To solve the problem, we have applied PSO based fitness enhancement. The results are compared with the classical algorithm available in the literature; the numerical results show that the modified algorithms outperform or perform better with the other algorithms.**

Keywords*-*Optimization, PSO, DOCR, power system protection

I. INTRODUCTION

Due to the rapid development of huge industrial systems, stability and security issues of power systems have recently acquired more attention. The basic function of protection systems is to detect and remove the faulty parts as fast and selectively as Possible [1, 2]. Coordination of protection is defined as the process of choosing settings or time delay characteristics of protective devices such that the operation of the devices will occur in a specified order to minimize customer service interruption, reduce equipment damage, or personal injury [3]. The aim of relay coordination in power systems is to quickly isolate fault areas to preserve service throughout most of the power systems [1]. Each protection relay needs to be coordinated with the relays protecting adjacent equipment. Hence, relays should not only be correctly operated, but also properly coordinated with each other by finding optimum relay settings. During the operation of a modern interconnected power system, abnormal conditions (faults, overload, over-voltage, under-frequency, etc.) can frequently occur. Such conditions cause interruption of the supply, and may damage the equipments connected to the system, arising the importance of designing a reliable protective system. In order to achieve such reliability, a back-up protective scheme is provided to act as the second line of defence in case of any failure in the primary protection (the first line of defence). To insure reliability of the protective system, the back-up scheme shouldn't come in to action unless the primary (main) fails to take the appropriate action. In other words, it should operate after a certain time delay known as coordination time interval (CTI), giving the chance for the primary protection to operate.

The for mentioned situation leads to the formulation of the well-known protective relay setting coordination, that consists of the selection of a suitable setting of each relay such that their fundamental protective function is met under the desirable qualities of protective relaying, namely sensitivity, selectivity, reliability, and speed [7]. In the past four decades, several efforts has been devoted to the automation of the coordination process of directional overcurrent relays (DOCR) and distance relays in interconnected power networks using digital computers. Traditionally, to solve such problem the trial and error approach was used, but it suffered a slow rate of convergence, due to the large number of iterations needed to reach a suitable relay setting. In a trial to minimize the number of iterations needed for the coordination process, a technique to break all the loops at the so-called "break points" and locate the starting relays at these points (where the coordination process starts) is suggested. Topological methods, including graph theory and functional dependency, are used to determine the break points [5]–[7]. It is important to mention that the solution found using topological methods is the best of the alternative settings considered, but not optimal in any strict sense. In other words the time dial settings of the relays are relatively high. In the year 1988, the coordination of DOCR in the frame of the optimization theory was reported [11]. The values of the time dial setting (TDS) have been calculated using LP (simplex method) for a given values of the pick-up currents. Recently, the interest in applying artificial intelligence (AI) in optimization has grown rapidly. Genetic algorithm [12] and evolutionary algorithm [10] have been used in the literature to find an optimal setting of the protective relays.

II Literature review

Before the application of optimization theory in these problems, trial and error approach was used but it has a well known drawback of slow convergence rate as a result of large number of iterations needed to reach a suitable relay setting. To overcome the disadvantage of trial and error method, many authors assumed the value of DOCR settings based on expert's experience and solved them in a linear environment (Irving and Elrafie, 1993; Chattopadhyay et al., 1996; Urdaneta et al., 1996; Urdaneta et al., 2001). However, it was observed that linear approach cannot ensure correct settings of the relays (Laway and Gupta, 1993) as it did not consider all possible operating conditions of the power system. Urdaneta et al. (1988) was the first to report the application of optimization theory in the coordination of DOCR. A detailed literature survey on this problem has been performed by (Birla et al., 2005). They have classified the previous works on DOCR coordination into three categories: curve fitting technique, graph theoretical technique and optimization technique. Sparse dual revised simplex method of linear programming has been used in (Irving and Elrafie, 1993) to optimize the TDS settings for assumed non-linear PS settings. Some linear programming techniques applied in DOCR coordination problem include Chattopadhyay et al. (1996); Urdaneta et al. (1996); Braga and Saraiva (1996); Abyaneh and Keyhani (1995); and Abdelaziz et al. (2002). Laway and Gupta (1993) applied simplex and Rosenbrock Hillclimb methods to optimize the TDS and the PS settings, respectively, in a similar way, as used by Urdaneta et al. (1988). The optimization of DOCR settings using artificial intelligence (AI) and nature inspired algorithms (NIA) has received considerable attention recently. Some of the NIA algorithms like evolutionary programming (So and Li, 2000a), genetic algorithm (GA) (So et al., 1997; Razavi et al., 2008; Thakur, 2007), modified evolutionary programming (So and Li, 2000b, 2004), and particle swarm optimization (Mansour and Mekhamer, 2007; Zeineldin et al., 2006; Bansal and Deep, 2008) have been applied successfully for solving this problem. Self organizing migrating algorithm (SOMA) and its hybridization with GA have been applied by (Dipti, 2007). Some of the AI methods like fuzzy logic (Abyane et al., 1997) and expert systems (Brown and Tyle, 1986; Lee et al., 1989; Hong et al., 1991; Jianping and Trecat, 1996) have also been applied to this problem. Birla et al (2006) and Deep et al (2006) used random search technique (RST2) to solve the relay coordination problem for IEEE 6-bus model and IEEE 3-bus, 4-bus models, respectively. Although DE is a robust and a popular optimization tool for solving complex optimization problems, as far as authors know no research paper is available on the implementation of DE for optimization of DOCR settings. In this paper an effort has been made to apply DE and its modified versions on the above mentioned problem of DOCR settings and the results are compared with other contemporary algorithms.

III. DOCR COORDINATION PROBLEM OPTIMIZATION:

Problem statement:

The present work aims to determine the minimum operating time of all power system primary over current relays. Therefore the power system equipments and stability are protected and achieved respectively. To estimate the minimum operating time of all relays, an object function for relays operating times is developed under some constrains.

DOCR coordination problem is a parametric optimization problem, where different constraints have to be considered in solving the objective function. Here the objective function to be minimized is the sum of the operating times of the relays connected to the system, subject to the following constraints.

A. Relay Characteristics:

A typical inverse time directional over current relay has two units, an instantaneous unit (time independent) and an inverse over current unit (time dependent). The time dependent unit has two values to be set, the pickup current (Ip) and the time dial setting (TDS). The pickup value is the minimum value of current for which the relay operates. The time dial setting defines the operating time (T) of the relay for each current value [11]. The characteristics of the OCR are given as a curve of T versus M, where, i.e.

$$M = I/IP \qquad (1)$$

Where I is the relay current (overload/fault current). M is a multiple of the pickup current and IP is the pickup current

Here the overcurrent relay is conformed to the following IEC characteristic [12, 13]. The following formula is used to approximately represent the inverse overcurrent relay characteristics.

$$T_{i,\,k} = k_1.TDS/\,(M^{k2}-1) \qquad (2)$$

Where k1 and k2 are constants that depend on the relay characteristics. The relation between the operating time (T) of the time overcurrent unit and the multiple of pickup current (M), is nonlinear. The multiple of pickup current of the relays can be predetermined and so for a fixed M, the above equation can be rewritten as

$$T_{i,\,k}=a.TDS \qquad (3)$$

Where $a = \frac{K_1}{M^{K_2-1}}$

*B. Relay Settings***:**

The calculation of the two settings, TDS and Ip, is the essence of the directional Overcurrent relay coordination study. It is very important to mention that in general, directional overcurrent relays allow for continuous time dial settings but discrete (rather than continuous) pickup current settings [12]. Therefore this constraint can be formulated as:

$$TDS_{i_{min}} \leq TDS_i \leq TDS_{i_{max}}$$

$$I_{pi\,min} \leq I_{pi} \leq I_{pi\,max}$$

C. Coordination Formulation:

In any power system, a primary protection has its own backup one for guaranteeing a dependable power system. The two protective systems (primary and back-up) should be coordinated together. Coordination time interval (CTI) is the criteria to be considered for coordination. It's a predefined coordination time interval and it depends on the type of relays. For electromagnetic , CTI is of the order of 0.3 to 0.4 s, while for a microprocessor based relay, it is of the order of 0.1 to 0.2 s. To ensure reliability of the protective system, the back-up scheme shouldn't come into action unless the primary (main) fails to take the appropriate action. Only when CTI is exceeded, backup relay should come into action [13 - 15]. This case is expressed as

$$T_{backup} - T_{primary} \geq CTI$$

Where T_{backup} is the operating time of the backup relay. $T_{primary}$ is the operating time of the primary relay. After considering all these criteria, this problem can be formulated mathematically as-

$$J = \min\left[\left(\alpha_1 * \sum_{i=1}^{N_r} T_{i,k}\right) + \sum_{P=1}^{PR} (Penality)^P\right] \qquad (4)$$

The second term in (4) maintains the CTI greater than 0.2 s.If CTI is below 0.2 s; a very high penalty is generated as per (5) and is added in the fitness function given in (4). If there is no CTI violation, then zero penalties are added in (4) as per (5). In this way penalty is calculated for each primary/backup over current relay pair 'PR'. The expression for k is given in (6).

$$Penality = \{k, \forall \Delta t_{mb,k} < 0. \, else \;\; 0 \qquad (5)$$

$$k = \alpha_2 * |0.2 - \Delta t_{mb,k}|^2 * (\Delta t_{mb,k} < 0.2) \qquad (6)$$

Where $\Delta t_{mb,k}$ is selectivity margin and also known as CTI and is α_2 weighting parameter used for controlling lower limit of CTI above0.2 s.Where i=1 to N_r, represents the number of relays [16, 17, 18].

IV. PARTICLE SWARM OPTIMIZATION

PSO is a population based stochastic search technique, originated from the social behaviour of birds and fishes within a flock and school respectively. This method was first introduced as an optimization technique for continuous nonlinear programming problems by J. Kennedy and R. Eberhart in 1995.The main concept of PSO algorithm is based on the maintenance of a population of particles commonly mentioned as "swarm", where each particle represents a candidate solution for the considered optimization problem. In each iteration, the particles are able to memorize their position and update their velocity, combining the current velocity, their best position visited during the journey in the problem search space, referred to as "personal best (pbest)" position and also the best state among all particles' pbest positions, called "global best (gbest)" position. [19]

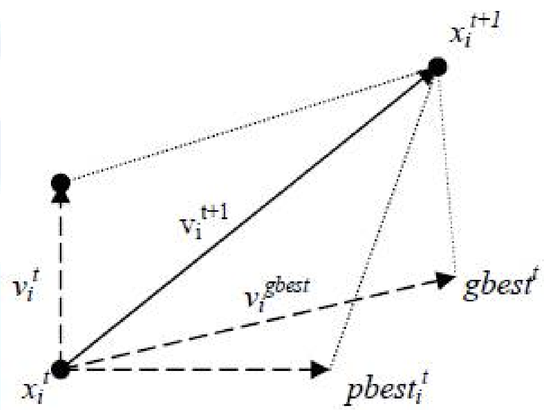

Fig-1 search mechanism of the PSO

Main Advantages of PSO-based Approaches:

a) A derivative-free technique

b) Easy in its concept and coding implementation

c) Less sensitive to the nature of the objective function

d) Limited number of parameters. Also, less sensitive to parameters

e) Less dependent on initial points

f) Generate high-quality solutions with shorter calculation time and stable convergence characteristics

Application of PSO:

PSO has been successfully applied in many areas function optimizations, neural network training, Object tracking, path planning, signal processing, image processing, fuzzy system control and other areas where GA can be applied.

Algorithm of PSO:

PSO1: Initialize positions and associated velocity of all particles (potential solutions) in the population randomly in the D dimension space.

PS02: Evaluate the fitness value of all particles.

PS03: Compare the PBEST of every particle with its current fitness value. If the current fitness value is better, then assign the current fitness value to PBEST.

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PS04: Determine the current best fitness value in the whole population. If the current best fitness value is better than the GBEST, then assign the current best fitness value to GBEST.

PS05: Change velocities using t8he following equation:

V(t+1) id = w × vi(t) + c1 × rand() × (pbestid − S(t)id) + c2 × Rand() × (gbestd – S(t)id) (7)

Where
i=1, 2---- n; d=1, 2--- m.
'n' is the population size,
'm' is the number of units and
'w' value is set using:
$w = w_{max} - ((w_{max} - w_{min}) / itermax) \times iter$
where, $w_{max} = 0.9$; $w_{min} = 0.4$.
c1 and c2 are two positive constants, rand () are random function in the range [0,1].

Using the above equation, a certain velocity, which gradually gets close to pbest and gbest, can be calculated. The current position can be modified by the following equation:

S(t+1)id =S(t)id+ V (t+1) id (8)

PS06: Move each particle to S (t) id + V (t+1) id

PS07: Repeat steps PSO2-PSO6 until a stop criterion is satisfied OR a pre specified number of iterations is completed.

Results:

In this section the results are presented using PSO optimization method using the 8-bus, 9-branch network, taken from and shown in figure 1. This line diagram specifies the position of directional overcurrent relays. The algorithms utilizes the 8 bus system data implemented using the Microcontrollers using the relevant hardware circuits.

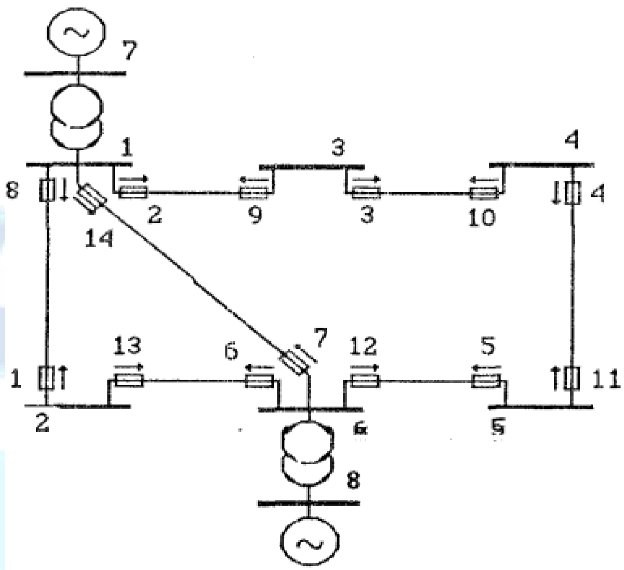

Fig 2. Eight Bus Systems

For the coordination problem of IEEE 8-bus model, value of each of N_{cl} and Nf_{ar} is 14 (equal to number of relays or twice the lines). Accordingly, there are 28 decision variables (two for each relay) in this problem i.e. TDS^1–TDS^{14} and PS^1–PS^{14}. Objective function (OBJ) to be minimized as given by-

$$OBJ = \sum_{i=1}^{6} T^{i}_{pri\_cl\_in} + \sum_{j=1}^{6} T^{j}_{pri\_for\_bus} \qquad (9)$$

Where

$$T^{i}_{pri\_cl\_in} = \frac{0.14 * TDS^{i}}{(\frac{a^{i}}{PS^{i} * b^{i}})^{0.02} - 1}$$

$$T^{i}_{pri-far\ bus} = \frac{0.14 * TDS^{i}}{\left(\frac{c^{i}}{PS^{i*d^{i}}}\right)^{0.02} - 1}$$

The values of constants a^i, b^i, c^i and d^i are given in the paper [20]. Constraints for the model Bounds on variables TDSs

$TDS^{i}_{min} \leq TDS^{i} \leq TDS^{i}_{max}$, where, i varies from 1to 14(N_{cl})

Bounds on variables PSs:

$PS^{i}_{min} \leq PS^{i} \leq PS^{i}_{max}$, where, i varies from 1to 14(N_{cl})

Limits on primary operation times:

This constraint imposes constraint on each term of objective function to lie between 0.05 and 1.0.

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The optimization process is run for 100 iterations and the final value of above mentioned fitness function is observed to be decreasing as shown in figure.

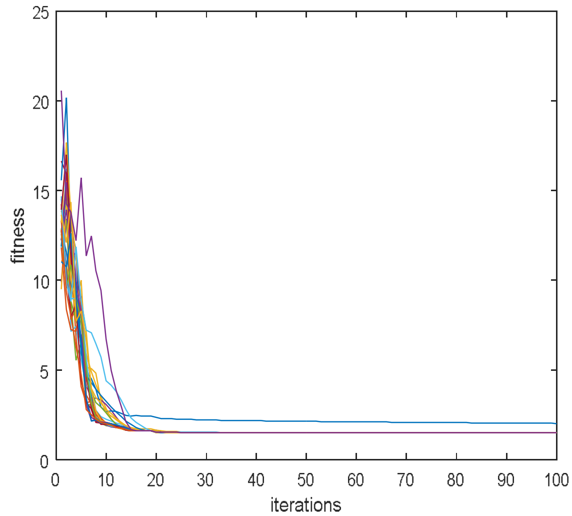

Figure 3: Convergence plot of PSO fitness cost function.

After the finish of optimization process the optimized solution in terms of TDS and PS are shown in figure 3.

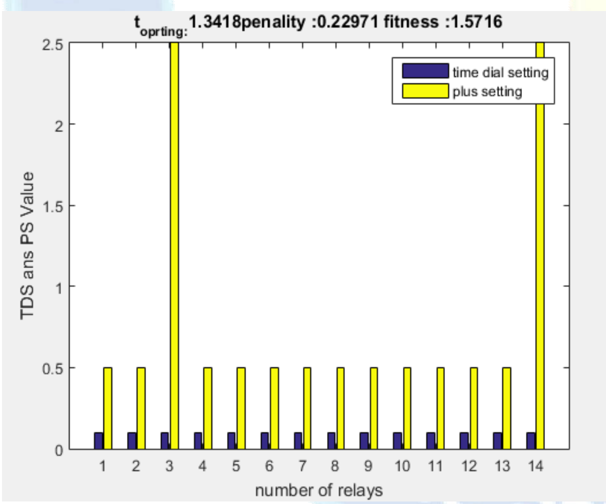

Figure 4: Penalty time and plug setting value for all relays

The values of TDS and PS are also given in the table1.

Table 1: Optimized operating times of relay using PSO

Relay	Primary(T)operating	Relay	Backup(T)operating
	time		time
1	0.20563	6	0.20563
2	0.17261	1	0.32382
2	0.17261	7	0.21443
3	0.17757	2	0.19964
4	0.19593	3	0.20304
5	0.2267	4	0.2267
6	0.17121	5	0.29739
6	0.17121	14	0.4463
7	0.16061	5	0.29739
7	0.16061	13	0.32525
8	0.17133	7	0.21443
8	0.17133	9	0.25441
9	0.19683	10	0.22408
10	0.19441	11	0.22859
11	0.19713	12	0.19713
12	0.17281	13	0.32525
12	0.17281	14	0.4463
13	0.21075	8	0.21075
14	0.26599	1	0.32382
14	0.26599	9	0.25441

Table 2: Fitness Value for optimized solution

conventionally result	**Result Using PSO**
Fitness=14.3501	Fitness=1.5716

Conclusion:

In this work, an optimization methodology is presented to solve the problem of coordinating directional overcurrent relays in an interconnected power system. The operating time of the relay was determined using MATLAB and is found to be 1.3418s and penalty factor is 0.22971 for Eight bus system. This value is optimized using Particle Swarm Optimization technique. A programming problem formulation is presented in this work for the optimal coordination of Directional over Current Relays. It is found that PSO requires 20 iteration at max for the optimization of the objective function. Therefore the proposed algorithm was used to obtain the optimal setting of the operation time of the directional over current relays in the case study system an 8-bus system. On studying these two cases and comparing the results with those obtained from previous works, it is seen that the objective function of the DOCR relay is minimized better. The optimization of the coordination of Directional over current relays can be further improved by considering or formulating new coordination constraints. Further, by improving the existing features of updating PSO technique, the optimization of relay coordination can be improved.

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